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Calibration and Equivalency Analysis of Image Plate Scanners

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We have developed a universal procedure to calibrate image plate scanners using radioisotope sources. Techniques to calibrate scanners and sources, as well as cross-calibrate scanner models, are described to convert image plate dosage into physical units. This allows for the direct comparison of quantitative data between any facility and scanner. We have also derived an empirical relation to establish sensitivity response settings for arbitrary gain settings. In practice, these methods may be extended to any image plate scanning system.

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I. INTRODUCTION

Radiation sensitive image plates, developed as an alternative to x-ray film for medical applications,[1,2] have been used extensively in experimental physics.[3,4] Image plate detectors are ideal for time integrated measurements due to their robustness against electromagnetic pulse, high dynamic range, linearity, and repeatability over a wide range of photon and particle energies. A significant body of x-ray[5–8], electron[9,10], and proton[11] sensitive data has been acquired for the purposes of calibrating image plates to extract quantitative information for high energy density physics (HEDP) experiments. Image plate scanner calibration is also necessary, as the absolute dosage absorbed by an image plate is a function of the scanner spatial resolution, digital precision, and sensitivity gain.

The active layer of an image plate consists of a phosphor crystal suspended in a binder. In the case of Fujifilm BAS-type image plate, the composition is $BaF(Br_x,I_{1-x}){:}Eu^{2+}$. Incident radiation further ionizes Eu^{2+} atoms and generates photoelectrons that remain in a metastable excited state. These electrons recombine through thermal excitation or after being stimulated (as is the case inside a scanner), emitting a blue photon ($\lambda \approx 390$ nm).[4] This process is called photostimulated luminescence (PSL). The blue light is then collected by a filtered photomultiplier tube (PMT) internal to the scanner and digitized in a two-dimensional image.

A change in manufacturer for a flatbed image plate scanner commonly used in HEDP experiments has prompted this work to establish a universal method to accurately calibrate individual scanners and perform cross-calibrations between scanning systems. In this paper, we present a method to recover physical units from, and calibrate sensitivity settings for, image plate scanner systems. Three techniques are described to calibrate scanners by using either a source of known dosage, by using a secondary pre-calibrated scanner with an arbitrary-strength source, or by using cross-calibrated sources of known and unknown image plate dosages. In principle, these necessary calibration procedures could be applicable to an image plate scanner of any make or model. Part II describes a procedure that calibrated a scanner with a radiocarbon source of known activity and image plate response. Part III includes a method that calibrated a scanner using a second, pre-calibrated scanner and an ^{55}Fe radioisotope with unknown image plate response. Part IV describes a method that cross-calibrated a radiocarbon source with a secondary ^{14}C source and was subsequently used to determine the calibration parameters for a scanner to recover physical units at arbitrary sensitivity settings.

II. CALIBRATION USING KNOWN SOURCE

A calibration source with known energy deposition was used to calibrate image plate scanners located at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL). This procedure exposes an image plate to a radiocarbon source for a fixed time to yield a known absorbed dose. The plate is then scanned on an uncalibrated scanner to calculate the necessary correction factor. Here, we cut a 7×7 cm^2 piece of new and erased image plate of type Fujifilm BAS-MS and exposed it to a ^{14}C impregnated polymethylmethacrylate plastic disc sealed source (referred to here as Source A) with a 1 cm diameter active area containing uniformly distributed polymer of 10 μCi/g with a total activity of 60 μCi.[8] The image plate was in direct contact with Source A for 20 minutes then placed into a light-tight container at room temperature to rest for 5 minutes. After the wait period, the plate was scanned using a GE Typhoon 7000 flatbed image plate scanner at a spatial resolution of 50 μm.

Exposures were repeated and image plates were scanned for a range of sensitivity settings by incrementing the PMT gain voltage from 500 to 1000 V. The resulting scanned images showed high spatial uniformity and mean image values per unit area over the exposure

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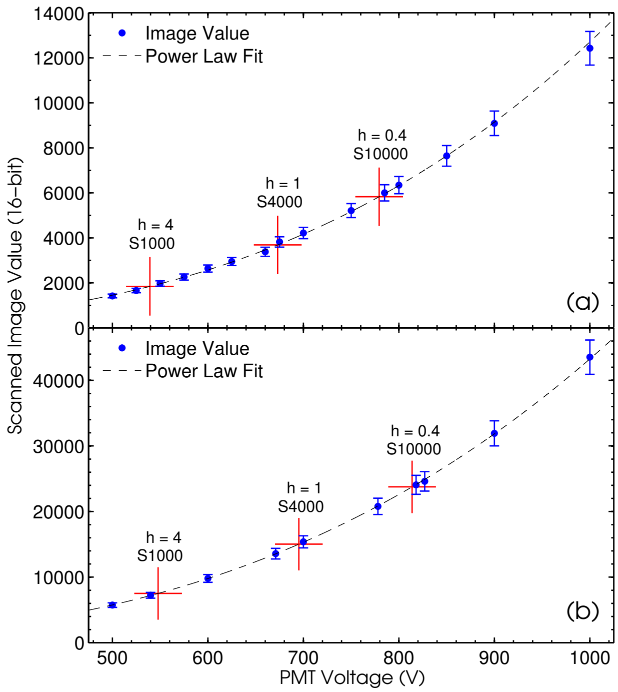

FIG. 1. (Color online) Averaged image values from GE Typhoon 7000 scanners as a function of photomultiplier tube voltage for multiple exposures. A power law fit (dashed) to experimental data resolves equivalent-sensitivity voltages (solid) for GE Typhoon scanners located at NIF (a) and LLE (b) using ^{14}C and ^{55}Fe sources respectively. The ^{55}Fe source is significantly stronger than the ^{14}C.

surface were recorded as a function of gain settings. Figure 1a shows average image values for increasing PMT voltage for a single scanner at the NIF. To linearize the image values, a relation was derived, specific to the GE scanning system,

$$\mathrm{PSL_{GE}} = \left(\frac{G}{2^{16}-1}\right)^2 \left(\frac{R_{\mu\mathrm{m}}}{100}\right)^2 h(V)\ 10^{L/2} \qquad (1)$$

where $R_{\mu m}$ is the spatial resolution in μm, L is the dynamic range latitude (either 4 or 5 orders of magnitude), and G is the scanned image value. The sensitivity function, $h(V)$, is an empirical relation found by solving Eq. (1), using the known image plate response. Source A has a known value of 100 PSL/mm^2 (scanned mean image value is 0.25 PSL), for a 50 μm spatial resolution. This value was found by performing the above exposure procedure on a scanner immediately after it had been serviced by a technician.

A power law fit of the form $G = aV^b$ was fit to the scanned image value verse PMT voltage shown in Fig. 1a where $a = 5.26 \times 10^{-6}$ and $b = 3.13$. Image values were calculated using $h(V) = 4$, 1, and 0.4, which corresponds to the three discrete Fuji-brand sensitivity settings of $S1000$, $S4000$, or $S10000$ respectively to be 539.3 V, 673.1 V, and 779.3 V.

TABLE I. Equivalent-sensitivity settings for three GE Typhoon 7000 image plate scanners located at the NIF. The PMT gain curve for Scanner 1 does not allow for an $h = 4$ equivalent due to the 500 V lower limit where an equivalent sensitivity value is noted.

	$h = 4$	$h = 1$	$h = 0.4$
Scanner 1 Voltage (V)	500 ($h = 3.15$)	588	678
Scanner 2 Voltage (V)	527	633	728
Scanner 3 Voltage (V)	539	673	779

Several of the GE scanners tested were unable to achieve an $h = 4$ equivalent voltage. This is due to a lower PMT voltage limit of $V = 500$ V set in the scanning control software. In these cases we have defined a new equivalent-sensitivity setting that corresponds to $V = 500$ V to create continuity with existing analysis tools. This designation simplifies any adaptation in the post processing of files by simply exchanging sensitivity values. Table I gives a list of PMT voltage settings and corresponding sensitivities for three NIF scanners along with the lower-limit equivalents in the case where the 500 V limit was reached. The large sensitivity discrepancies between scanners underscores the necessity to calibrate each scanner, ideally at regular intervals as a scanner maintenance procedure. It has been found that some scanners are in need of recalibration after only three months.

III. CALIBRATION USING ARBITRARY SOURCE AND A CALIBRATED SECONDARY SCANNER

An image plate scanner was calibrated using a secondary calibrated scanner and an ^{55}Fe source, Source B, of unknown image plate response at the Laboratory for Laser Energetics (LLE) at the University of Rochester. In this method, a calibrated Fuji FLA 7000 scanner and uncalibrated GE Typhoon 7000 scanner were used. A single image plate of Fujifilm type BAS-MS was exposed to Source B, a 3 mm thick, 12.5 mm diameter ^{55}Fe sealed source in a shielded enclosure with a 1 mm polycarbonate front filter that had a dose rate of 1.4 mrem/h, measured on contact. The source assembly was placed 7.0 cm above the image plate which was then exposed for 5 min followed by an additional 30 min in a light tight enclosure at room temperature before being scanned in either the calibrated or uncalibrated scanner using a resolution of 50 μm.

As a control, a measure of the repeatability and linearity of scanning parameters was performed on the calibrated Fuji scanner. Four exposures were scanned at each of the three sensitivity settings where the resulting

TABLE II. Summary of cross-calibration scans between Source A and Source C. The recorded dosage on the JLF scanner was scaled by 17.2% to maintain consistency with the expected calibrated dosage of 100 PSL/mm^2. Scanned dosage readout was assumed to be linear so that the same procedure could be repeated for Source C to recover a corrected calibrated dosage.

Source Activity (μCi/g)	Recorded Dosage (PSL/mm^2)	Calibrated Dosage (PSL/mm^2)
Source A	117.2 ± 9.3	100.0 ± 13.2
400	1051.2 ± 74.8	896.9 ± 96.0
280	835.2 ± 50.8	712.6 ± 71.6
220	662.0 ± 40.0	564.8 ± 56.6
117	364.8 ± 29.2	311.3 ± 35.2
51.6	184.8 ± 14.8	157.7 ± 17.8
35.0	104.0 ± 8.3	88.7 ± 10.0
18.4	76.8 ± 6.1	65.5 ± 7.4

image plate response was measured to be 1588.4 ± 14.6 PSL/mm^2, 1662.6 ± 23.9 PSL/mm^2, and 1706.5 ± 20.0 PSL/mm^2 for sensitivity settings of $S1000$, $S4000$, and $S10000$ respectively. The systematic nonlinearity in scanned response is small and well within the $\sim 8\%$ calibration tolerance set by the manufacturer.

Exposures were again performed for the range of PMT gain voltages between 500 and 1000 V, with the results shown in Fig. 1b, and fit to a power law function of the form $G = aV^b$ gives $a = 8.10 \times 10^{-5}$ and $b = 2.90$. Equivalent-sensitivity voltages were found to be 547.9 V, 695.3 V, and 813.8 V for $h = 4$, $h = 1$, and $h = 0.4$, respectively.

IV. CALIBRATION OF SECONDARY SOURCE AND SCANNER

A. Cross-calibration of known and unknown source

A ^{14}C source, Source C, with unknown image plate response was cross-calibrated with Source A described in Part II. This procedure was developed to provide a dedicated scanner calibration source for facilities without previously calibrated sources or scanners. Source C has 16 ^{14}C polymer-embedded patches, each with a unique activity from 0.035 to 400 μCi/g, and a total activity of 20 μCi. The patches are 5×5 mm^2, and are adhered to a 3 in $\times$ 1 in $\times$ 0.5 mm sheet of plastic where each radioactive section has an approximate weight of 0.358 mg $\pm$ 10%.[12]

To map the source activity to image plate response, the exposure procedure described in Part II was followed, with 20 min of direct exposure on Fujifilm type BAS-MS and 5 min of rest time before scanning. Source A and Source C were placed on image plate cut from the same sheet then exposed and scanned together. A Fuji FLA 7000 scanner was used located at the Jupiter Laser Facility (JLF) at LLNL. From the scanned response of Source A, it was determined that the recorded signals were approximately 17% higher than expected. The image values of Source C were corrected to find the expected dosage in PSL for a set of 7 radiocarbon patches with the highest signal strength and spatial uniformity. A summary of the recorded and corrected dosages are shown in Table II. These calibrated dosages are the expected values that would be recorded from any calibrated image plate scanning system, regardless of make or model.

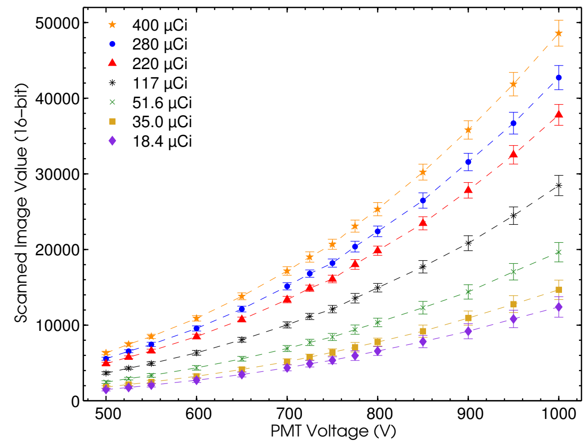

FIG. 2. (Color online) Scanner sensitivity response function for the GE Typhoon 7000 at ILE as a function of PMT voltage for 7 unique ^{14}C activity patches of Source C.

B. Calibration of scanner with empirical sensitivity function

A radiocarbon source was used to calibrate an image plate scanner and empirically derive a best-fit solution to the scanner sensitivity response function. Source C was used to calibrate a GE Typhoon 7000 scanner located at the Institute of Laser Engineering (ILE) at Osaka University. A series of image plate exposures were performed, identical to those described in Part II, for voltages from 500 to 1000 V with the same image plate used in Part IV A. The results of these scans are shown in Fig. 2 for the 7 activities listed in Table II.

Redefining Eq. 1 to include and solve for a sensitivity function dependent on PMT voltage, $h(V)$, gives

$$h(V) = \mathrm{PSL}_C^i \left(\frac{100}{R_{\mu\mathrm{m}}}\right)^2 \left(\frac{2^{16}-1}{G}\right)^2 10^{-L/2}, \quad (2)$$

where PSL_C^i is the calibrated dosage for the ith ^{14}C activity of Source C. Applying Eq. 2 to scanned image values provides a single set of weighted data corresponding to the sensitivity gain curve for the scanner at ILE (Fig. 3).

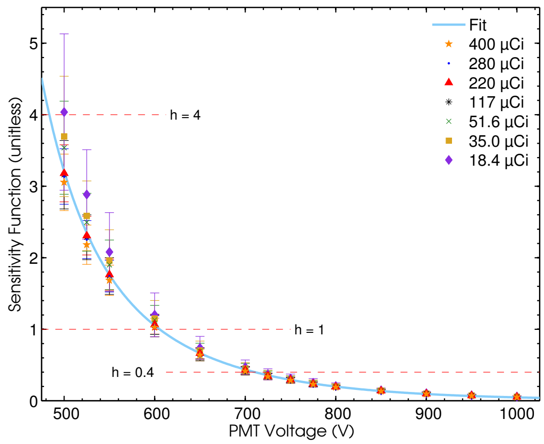

FIG. 3. (Color online) Image plate scanner sensitivity response as a function of PMT gain voltage for the GE Typhoon 7000 scanner at ILE. A weighted average is fit to a two-component exponential function (solid) such that a scan at arbitrary voltage may be expressed in physical units. Equivalent-sensitivity voltages are shown (dashed) corresponding to $h = 4$, 1, and 0.4.

A two-component exponential function of the form

$$h'(V) = A_0 + A_1 e^{-(V-V_0)/A_2} + A_3 e^{-(V-V_0)/A_4} \tag{3}$$

is fit to these data and the resulting parameters are given in Table III with $V_0 = 500$ V. A two-component exponential function was found to be the best-fit with the smallest residual error and is currently used to linearize scanned data to physical units for the ILE scanner.

As with the scanners at the NIF and LLE, equivalent sensitivities were found by solving for the voltage at which $h(V) = 4$, 1, and 0.4. The ILE scanner was unable to reach the $h = 4$ equivalent due to the PMT lower limit of 500 V. The equivalent sensitivity voltages were 500 V ($h = 3.21$), 605.4 V ($h = 1$), and 710.9 V ($h = 0.4$).

V. DISCUSSION AND CONCLUSION

Three techniques were presented and calibrations performed on image plate scanners using radioisotope sealed sources at the National Ignition Facility, the Laboratory for Laser Energetics, and at the Institute of Laser Engineering. Equivalent-sensitivity settings were found such that a direct comparison of recorded image plate signal can be made between different make and model scanners. These procedures are generic and can be applied immediately to any image plate scanning systems. A technique to recover physical units for continuous sensitivity settings was also described. A macro to convert from the compressed, GE scanning software export filetype, *.gel, to linearized PSL units has been written by the authors and is available upon request.

TABLE III. Fit parameters for a two-component exponential function for a fit to the experimental data in Fig. 3.

A_0 (PSL)	0.00800 ± 0.01326
A_1 (PSL)	1.2369 ± 0.2643
A_2 (V)	46.54 ± 5.37
A_3 (PSL)	1.967 ± 0.255
A_4 (V)	128.0 ± 10.6

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